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COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF PRESSURE EFFECTS IN A HOT CASCADE TYPE RANQUE-HILSCH VORTEX TUBE

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ABSTRACT

The vortex tube is a device, having no moving parts, which generates hot air and cold air simultaneously at its two ends from an inlet of compressed air. In this study, performance of hot cascade type Ranque-Hilsch vortex tube, with a length to diameter ratio (L/D) of 20 with different pressures 8, 9, 10, 11, and 12 bars, on the basis of CFD results were investigated. The total outlet hot kinetic exergy, total outlet hot physical exergy, total outlet cold kinetic exergy, total outlet cold physical exergy and total outlet exergy were investigated by using CFD software data. It was found that high total outlet exergy was obtained at the pressure of inlet air 12 bar.

KEYWORDS: Ranque-Hilsch Vortex Tube, Exergy, CFD & Straight Nozzles

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Original Article

INTRODUCTION

Refrigeration plays an important role in developing countries, primarily for the preservation of food, medicine, and for air conditioning. Conventional refrigeration systems are used Freon as refrigerant. As they are the main cause for depleting ozone layer, extensive research work is going on alternative refrigeration systems. Vortex tube is a non-conventional cooling device, having no moving parts which will produce cold air and hot air from the source of compressed air without affecting the environment. A vortex tube contains nozzles, vortex chamber, tube, cold end orifice and hot end control valve. In a vortex tube high pressure air is tangentially injected into vortex chamber, and lowering the pressure, it splits into a hot and cold temperature streams. Cold air stream leaves the tube through a center orifice near the entrance nozzle, while hot gas stream flows toward the control valve and leaves the tube. The vortex tube can be classified into two types: (i) counter-flow vortex tube (ii) uni-flow vortex tube, as shown in Figure 1a and b. In general, the counter-flow vortex tube is recommended over the uni-flow vortex tube for its efficient energy separation. Vortex tube can be used for any type of spot cooling or heating applications. In recent years, the techniques of Computational Fluid Dynamics (CFD) modelling have been developed for more survey and clarification. K. Dincer and Y. Yilmaz [1] investigated experimental investigation of performance of hot cascade type Ranque-Hilsch vortex tube (RHVT) and exergy analysis with regard to cold flow fraction. In this K. Dincer and Y. Yilmaz [1] have been examined three RHVTs experimentally. One of them is a classic RHVT. The other two are hot cascade type RHVT. In the hot cascade type RHVT, the heat output of first RHVT was connected to input of second RHVT. The temperature difference

between the hot outlet and inlet (ΔT_{hot}) values of hot cascade type RHVTs were greater than the ΔT_{hot} values of classic inlet (ΔT_{hot}) values of hot cascade type RHVTs were greater than the ΔT_{hot} values of classic RHVT. It was also found that, the hot cascade type RHVT more exergy efficiency of hot outlet than the classic RHVT. N. Pourmahmoud [2] carried out a computational fluid dynamics analysis of helical nozzles effects on the energy separation in a vortex tube. They showed that helical nozzle to form higher swirl velocity in the vortex chamber then the straight nozzle. K. Dincer [3] investigated experimental investigation of the effects of threefold type Ranque-Hilsch vortex tube and six cascade type Ranque-Hilsch vortex tube on the performance of counter flow Ranque-Hilsch vortex tubes. In this K. Dincer[3] have been investigated performances of RHVTs experimentally under three different situations based on inlet pressure and the ratio of mass flow rate of the cold stream to the mass flow rate of the inlet stream. 1st situation is the conventional RHVT. 2nd situation is the threefold cascade type RHVT. Here three RHVTs were used. 3rd situation deals with the six cascade type RHVT. In this case, six RHVTs were used. It was found that the best performance occurs in the 3rd situation at different pressures. S. E. Rafiee [4] was studied performance of vortex tube changing radius of rounding off edges at hot tube entrance using CFD analysis. They showed that the cold temperature difference has an increased at the radius of rounding off the edge in the range of 0-1.5 mm and decreased at the radius of rounding off tube length effect as a designing criterion.

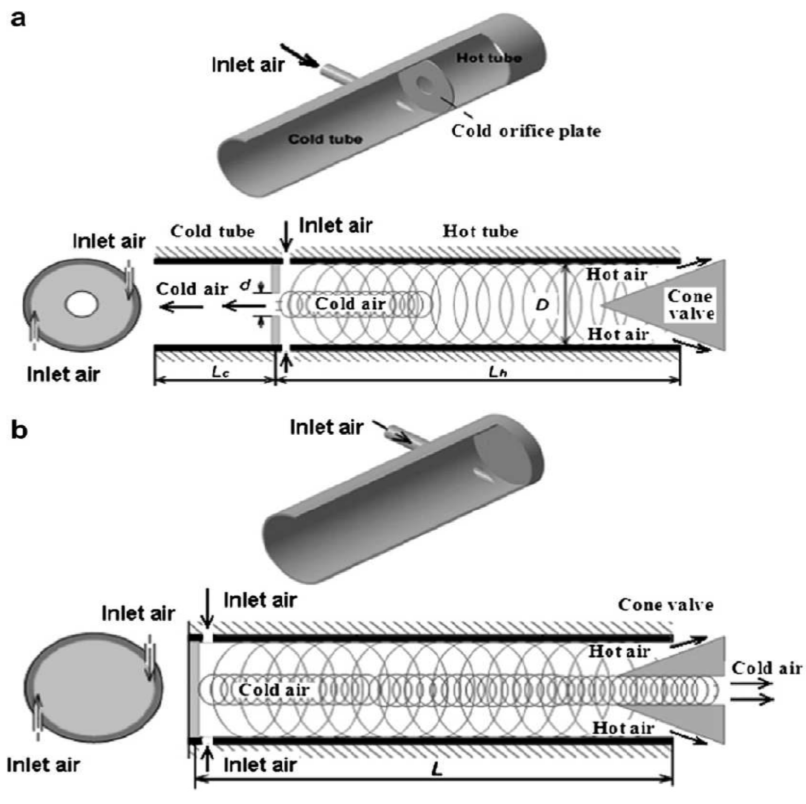

Figure 1: Ranque-Hilsch Vortex Tube for (a) Counter-Flow Type, (b) Uni-Flow Type (Eiamsa-ard et al., [17])

In this investigation have been carried out the effect of length and other parameters such as inlet pressure and nozzles on the behaviour of the vortex tube. Abdol Reza Bramo [6] carried out CFD simulations of length to diameter ratio effects on the energy separation in a vortex tube. In this numerical study, performance of RHVTs, with a length to diameter ratios of 8, 9.3, 10.5, 20.2, 30.7, and 35 with six straight nozzles were investigated. It was found that the best performance was obtained when the ratio of vortex tube length to the diameter was 9.3 and also fort this case the stagnation point was

found to be the farthest from the inlet. K. K. Zion [7] was investigated modelling and optimization of the vortex tube with CFD. In this investigation to study the influence of the length to diameter on the fluid flow characteristics inside the counter-flow RHVT predicted by CFD and validated through experiment. There are lots of studies in the literature about RHVT as the theoretical, analytical and experimental. Some of them are K. Dincer [8], H. Pouraria [9], W. Rattanongphisat [10], R. Oilver [11], and OnsTlili El May [12].

The Exergy of an energy form or a substance is a measure of its usefulness or the quality or potential change. Exergy is defined as the maximum work, which can be produced by a system or a flow of matter or energy and it comes to equilibrium with a specified reference environment i. e. dead state. Unlike energy, exergy is conserved only during ideal processes and destroyed due to irreversibilities in real processes (Prommas et al., [13]). Exergy analysis is a thermodynamic method of using the conservation of mass and energy principles together with the second law of thermodynamics for the design and analysis of thermal systems. The purpose of an exergy analysis is generally to identify the location, the source and magnitude of true thermodynamic inefficiencies in a given process (Casasa et al., [16]). Fuyuan Song [14] studied experimentally integrated vortex board with exergy analysis. In this combining with the experimental data, the exergy of the integrated vortex board was analysed, in view of the effect of inlet pressure, cold mass, diameter of outlet orifice, length of hot tube, structure of entrance nozzle on energy separation effect and exergy efficiency.

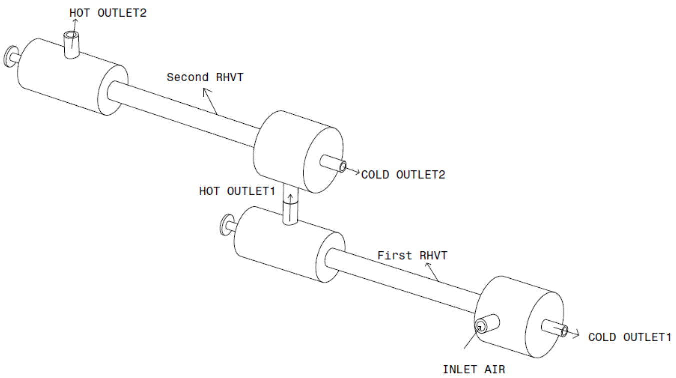

Figure 2: Schematic Diagram of the Hot Cascade Type Ranque-Hilsch Vortex Tube

COMPUTATIONAL FLUID DYNAMICS ANALYSIS

Governing Equations in Computational Fluid Dynamics

All of computational Fluid Dynamics, in one form or other is based on fundamental governing equations of fluid dynamics,

- Continuity Equation
- Momentum Equation
- Energy Equation

These equations speak physics of fluid flow. They are the mathematical statements of three fundamental physical principles upon which all fluid dynamics is based. Continuity equation is based on the principle of conservation of mass.

Net mass flow out of control volume = Time rate of decrease of mass inside control volume.

Momentum Equation is based on the law of conservation of momentum, which states that the net force acting on a fluid mass is equal to change in momentum of flow per unit time in that direction. The force acting on a fluid element mass 'm' given by Newton's second law of motion is:

F = m x a

Where 'a' is the acceleration acting in the same direction as force F.

Energy Equation is based on the principle that total energy is conserved.

Total energy entering control volume=Total energy leaving control volume.

CFD Model

In this investigation the ANSYS CFX 15.0 software package was used to create the CFD model of the hot cascade RHVT. In these two RHVTs was used. These two were hot cascade type RHVT. In the hot cascade type RHVT, the heat output of first RHVT was connected to input of second RHVT shown in the Figure 2. Two RHVTs, with an internal diameter of 6.75 mm and a length to diameter ratio of 20 were modelled and tested with air. Nozzle cross-section area = 3.141 mm^2 and number of nozzles is 6.

The models are three-dimensional steady state, axisymmetric, and employ the standard k-epsilon turbulence model. The three-dimension model is shown in Figure 3. The cold flow fraction (ξ) is defined as the ratio of the mass flow rate of the cold stream to the mass flow rate of the inlet stream. Flow was controlled by a valve on the hot outlet side. In this analysis pressure, temperature, and volumetric flow rate were recorded. These recorded data can be made by utilizing calculations.

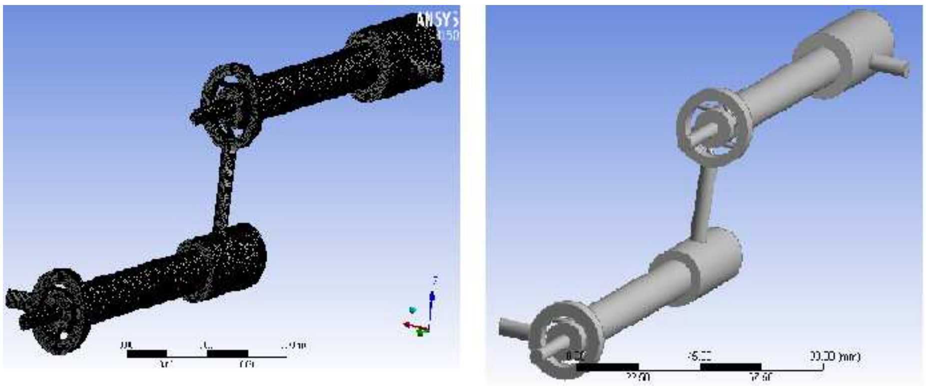

Figure 3: Three-Dimensional Model of Hot Cascade Ranque-Hilsch Vortex Tube

EXERGY ANALYSIS

The availability or exergy of a system in a given state is defined as the maximum reversible work that can be produced through interaction of the system with its surroundings as it reaches thermal, mechanical and chemical equilibrium. The following assumptions are made for the exergy analysis in hot cascade type RHVT system

- The reference to environmental temperature and pressure are considered as T_a= 301 K and P_a= 1.01325 bar.
- RHVTs do not exchange heat with the surroundings. The conditions of flow in a hot cascade type RHVT can be assumed adiabatic.

- Inlet and outlet gases were considered as ideal gases.

Physical Exergy (E_P) = m {C_P (T-T_a) - T_a [$C_P$ln (T/T_a) – R ln (P/P_a)]} (1)

Where m is mass flow rate, C_P is the specific heat at constant temperature, T_a and T are the initial and instant temperature, R is a gas constant, P_a and P are the initial and instant pressure.

Kinetic Exergy (E_K) = $mv^2/2$ (2)

Where v is velocity at that instant.

Total Outlet Exergy ($\sum E_o$) =$\sum E_{ohot}$+ $\sum E_{ocold}$

$\sum E_o = \sum E_{ohot,\,P} + \sum E_{ohot,\,K} + \sum E_{ocold,\,P} + \sum E_{ocold,\,K}$ (3)

Table 1: Exergy (E) for Different Values of Pressure (P)

P, bar	$E_{ohot\ K}$, W	$E_{ohot\ P}$, W	$E_{ocold\ K}$, W	$E_{ocold\ P}$, W	$\sum E_o$, W
8	162.78	1312.12	318.67	1059.57	2853.14
9	177.38	1351.44	339.84	1105.26	2973.92
10	192.23	1404.18	361.14	1165.18	3122.73
11	208.59	1450.98	383.78	1218.51	3261.86
12	223.89	1494.53	404.83	1256.97	3380.22

RESULTS AND DISCUSSIONS

In this study, the performance of hot cascade type RHVT was analysed by using ANSYS CFX 15.0 CFD software. In these two RHVTs was used. These two were hot cascade type RHVT. In the hot cascade type RHVT, the heat output of first RHVT was connected to input of second RHVT. In hot cascade type RHVT were modelled as a cold mass fraction (ξ) was controlled by the hot stream of the first and second RHVTS ξ = 0.5 and the performance was analysed**.**

In this study, exergy analysis was made by using the obtained CFD results data. The quantity of $\sum E_{ohot\ K}$,$\sum E_{ohot\ P}$,$\sum E_{ocold\ K}$,$\sum E_{ocold\ P}$, and $\sum E_o$ were calculated from Eqs. (1), (2), and (3) respectively. Figure 4a, b, and c were showing the variations of $\sum E_{ohot,}$ $\sum E_{ocold,}$ and $\sum E_o$ with respect to P. According to the CFD results maximum values of $\sum E_{ohot}$ = 1718.12 W was obtained at P= 12 bar, $\sum E_{ocold}$ = 1661.8 W was obtained at P= 12 bar, and $\sum E_0$ = 3380.22 W was obtained at P= 12 bar.

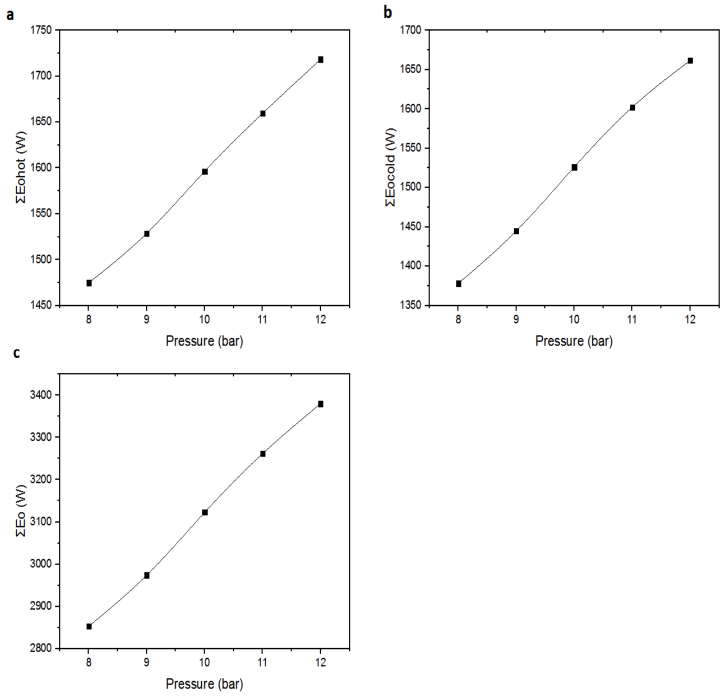

Figure 4: (a) $\sum E_{ohot}$ for Different Values of Pressure (b) $\sum E_{ocold}$ for Different Values of Pressure (c) $\sum E_o$ for Different Values of Pressure

CONCLUSIONS

The conclusions drawn from this paper are summarized as follows:

- In the hot cascade type RHVT, the kinetic exergy of the hot stream increased while the kinetic exergy of the cold stream increased with respect to pressure. However, the kinetic exergy of the inlet stream did not change (Table 1).
- In the hot cascade type RHVT, the physical exergy of the hot stream increased while the physical exergy of the cold stream increased with respect to pressure. However, the physical exergy of the inlet stream did not change.

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